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——《数据与决策》系列报告

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Health Benefit of Air Quality Improvement in Guangzhou, China Results From A Long Time-series Analysis（2006 — 2016）

我国典型地区空气质量改善的健康效益评估及人群健康防护策略研究课题组

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简介

国家自然科学基金—北京大学管理科学数据中心 (Data Center for Management Science, NSFC-PKU) 成立于 2014 年 12 月，是由国家自然科学基金支持，服务全国管理科学的数据收集与数据服务中心。作为北京大学直属的、以交叉学科为特点的实体学术科研机构，中心长期开展以中国家庭追踪调查（China Family Panel Studies, CFPS）、中国健康与养老追踪调查（China Health and Retirement Longitudinal Study, CHARLS）为代表的一系列大样本、高质量的微观调查数据收集。自成立以来，数据中心借助已有优势，逐步推进数据采集、数据管理与服务和智库研究三个领域的建设。

中心智库以构建开放性的、跨学科研究平台为目标，旨在大力推动运用科学的量化研究方法，以开发和利用 CFPS、CHARLS 等优质数据资源为基础的量化研究，并针对国家经济和社会管理的重大需求，积极为国家发展提供有实证依据的政策建议。

中心智库每年通过公开竞标方式，择优资助若干研究课题，为立项课题提供研究资金、研究助理和办公空间等多方面支持，并借助智库平台对相关研究成果进行推广。此外，中心智库推出客座研究员项目，诚邀有志从事与政策相关的数据研究的学者们驻中心研究。客座研究员可得到数据服务及办公条件的支持，并参与中心组织的各类学术研讨活动。

同时，中心智库通过研讨会、公开讲座等学术活动，促进知识分享和研究成果交流。中心智库还推出《数据与决策》系列出版物，包括《数据与决策：工作论文》、《数据与决策：政策报告》、《数据与决策：政策简讯》，旨在为以数据为基础的科学研究与政策研究的学者提供互动交流的平台。

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Abstract

Numerous epidemiologic studies on adverse health effects of air pollution have been well documented; however, assessment on health benefits of air quality improvement from air pollution control measures has been limited in developing countries.

We assessed the mortality benefits associated with air pollution improvement over 11 years in Guangzhou, China (2006-2016).

A time series analysis with Generalized additive Poisson models was used to estimate mortality effects of ozone (O3) and nitrogen dioxide (NO2), adjusting for time trend, day of week, public holiday, temperature and relative humidity. We further estimated the changes in mortality burden of O3 and NO2, including attributable fraction (AF, in %) and attributable mortality (AM, in number of death) during study period. We lastly estimated mortality effects during the 2010 Asian Games (November 12 to December 18, 2010) compared to a baseline period consisting of 4-week before and 4-week after the game.

During the study period, average annual concentrations of NO2 decreased from 42.3 μg/m3 in 2006 to 33.8 μg/m3 in 2016; while O3 levels remained stable over time. We observed significant increases in mortality of O3 and NO2, with approximately linear exposure-response relationships. In specific, each increase of 10 μg/m3 in O3 and NO2 at 2 prior days was associated with increases of 0.60% (95% confidence interval (CI): 0.47, 0.74) and 1.89% (95%CI: 1.49, 2.29) in total mortality, respectively. We further estimated that AF on total mortality attributed to NO2 decreased from 1.38% (95%CI: 1.09, 1.68) in 2006-2010 to 0.43% (95%CI: 0.34, 0.52) in 2011-2016, corresponding to AM on total mortality of 2496 deaths (95%CI: 1964, 3033) to 1073 deaths (95%CI: 846, 1301). During the 2010 Asian Games, we observed decrease in total mortality of 9.3% (95%CI: -15.0, -3.2) in comparison with that observed in the baseline period. Similar mortality benefits in cardiovascular diseases were also observed.

Our results showed reduced mortality burden from air pollution improvement in Guangzhou in recent years, which provide strong rationale for continuing to reduce air pollution through comprehensive and rigorous air quality management in the area.

Keywords: air quality improvement mortality burden health benefit Asian Games time-series analysis

1. Introduction

Numerous epidemiological studies have demonstrated the associations between air pollution and cardio-respiratory morbidity or mortality (Chen et al. 2017; Di et al. 2017; Samet et al. 2000; Zanobetti and Schwartz 2009). Majority of these studies are conducted in metropolitan cities in developed countries, with the well-established air pollution monitoring system and lower air pollutant levels (Di et al. 2017; Schwartz et al. 2017; Zanobetti and Schwartz 2009). Further, even in these regions, the implementation of increasingly stringent air pollution control policies and legislations have resulted in large reductions in disease burden attributing to ambient air pollution improvement. However, studies on health effects of air pollution and the assessment on health benefits of air quality improvement from air pollution control measures based on long-term time series in highly polluted regions (e.g., Asian) are still limited, largely may due to sparse historical air pollution data and monitoring network (Sun et al. 2018; Wong et al. 2008; Yin et al. 2017).

China is one of the countries with severe air pollution due to rapid economic development and urbanization in the past decades (Chen et al. 2011; Shang et al. 2013). Under this grim situation, a series of progressive air pollution control measures and policies have been implemented for improving air quality throughout the country in recent years (Bao et al. 2015; Cheng et al. 2013; Fang et al. 2016; Liu et al. 2018). For example, the National Ambient Air Quality Standards (NAAQS) was prompted in 2012 for stringent air pollutant standards (MEE 2012), following a series of major air quality regulatory measures to reduce air pollution emissions.

Systematic and strategic multi-pollutant control actions and policies have also been initiated and implemented for air quality improvement in the Pearl River Delta (PRD) region in southern China, including the capital city of Guangzhou (Huang et al. 2018; Zhong et al. 2013). In recent years, a series of rigorous air pollution control measures have been implemented, including Air Pollution Comprehensive Treatment Programme (GZMG 2008), Air Pollution Integrated Control Work Plan (2014-2016) (GEP 2014), as well as its routine five-year environment protection plans and actions (GZMG 2013, 2016). Thus, several previous studies have reported the effectiveness of air quality improvement in Guangzhou, such as reductions in concentrations of particulate matter (PM) and nitrogen dioxide (NO_2) (GDEMC 2017; Liu et al. 2013; Zhong et al. 2013); whereas serious ozone (O_3) pollution remained in recent years, such that daily maximum 8-hour averages with the 90^{th} percentile of year increased from 155 μg/m^3 in 2016 to 162 μg/m^3 in 2017 in Guangzhou (GEP 2017). The levels of volatile organic compounds (VOCs) appeared to be increasing that might resulted in the elevation in O_3 levels in Guangzhou (Ou et al. 2015). Therefore, more rigorous pollution control actions are currently underway targeting VOCs and O_3 reduction, including Clear Air Action Plan in PRD and Guangdong Province Air Pollution Prevention and Control Plan, with summary details shown in **Table S1**.

We have previously reported significant associations between ambient oxidants (O_3 and NO_2) and mortality in PRD (2006-2008), which called for pollution reduction efforts to reduce ambient air pollution attributed mortality risks (Tao et al. 2011; Tao et al. 2012). Therefore, to continue on data collection and in present analyses, a 11-year daily mortality and air pollution time-series data provided a unique opportunity to examine potential health benefit of air quality changes in Guangzhou (2006-2016). In this updated analysis, we hypothesized that ambient air pollution would be associated with increased mortality risks, and mortality burden attributed to locally predominate pollutants O_3 and NO_2 would be reduced resulting from significant air quality improvement over time. We further examined potential health benefits from air pollution reduction during the 2010 Asian Games (November 12 to December 18, 2010) in Guangzhou, compared with a wintertime baseline period consisting of 4-week before and 4-week after the Games.

2. Materials and methods

Study setting

Guangzhou is the capital of Guangdong province and located at the center of the PRD region in southern China, which is one of important regional commercial and financial development center with 14.5 million resident population in 2017. Ambient air pollutants tend to be accumulated due to subtropical humid monsoon climate of wet and hot months, cool to mild months, and seasonal variations in wind directions in Guangzhou (Wu et al. 2018).

Mortality data

We obtained daily mortality counts from January 1, 2006 to December 31, 2016 with information on identification number, underlying cause of death and date of death from Government Affairs Service Center of Health Department of Guangdong Province. We classified mortality outcomes by the *International Classification of*

Diseases, 10th Revision (ICD-10) and divided into following causal categories: total (non-accidental) mortality (ICD-10: A00-R99), cardiovascular mortality (ICD-10: I00-I99) and respiratory mortality (ICD-10: J00-J98) for all ages.

Environmental data

We obtained hourly concentrations of O_3, NO_2, $PM_{2.5}$ (μg/m^3) from three air monitoring stations in Guangzhou, including the station of Luhu (23.15°N, 113.28°E), Tianhu (23.65°N, 113.62°E) and Wanqingsha (22.75°N, 113.61°E), which had been operated and measured from Guangdong Environment Monitoring Center since early 2000's (**Figure S1**). The three stations were all with distance to busy traffic and industrial sources reflecting background air pollution levels situation in the area. We calculated daily concentrations of maximum 8-hour O_3, NO_2 and $PM_{2.5}$, which had been described elsewhere (Tao et al. 2012; Wu et al. 2018). We also obtained daily temperature (°C) and relative humidity (RH, %) data for a fixed station locating in Liwan district (23.08°N, 113.19°E) at the same period from Chinese Academy of Meteorological Sciences.

Statistical analysis

We assessed the short-term mortality effects for O_3 and NO_2 using generalized additive models (GAM) with a quasi-Poisson link to account for over-dispersion adjusted for time trend, temperature and RH, day of the week (DOW), public holidays, influenza epidemics and offset of annual population (Burnett et al. 2004; Costa et al. 2017; Tao et al. 2012; Wu et al. 2018). In specific, we used natural splines function with 8 degrees of freedom (DF) to control for time trend (Samoli et al. 2013; Wu et al. 2018). Temperature and RH at 1 day prior to death (lag1) with natural splines function were controlled according to minimizing Akaike's information criterion (Tao et al. 2012). The specific DF for time trend, temperature and RH were shown in **Table S2.** 6 DF were chosen for temperature and RH for total mortality. Other variables including DOW, public holidays and influenza epidemics were treated as dummy variables into models. Influenza epidemics were assigned as 1, when 7-day moving average of daily respiratory mortality counts were greater than the 90^{th} percentile of its time-series distribution, or 0 otherwise (Tao et al. 2012). Further, the demographic data of study population in Guangzhou were collected from Guangzhou Statistical Bureau (GZSB, http://www.gzstats.gov.cn/). We included the logarithm of annual total population by year to control for potential effects of population shifts in Guangzhou over time (Lin et al. 2016c; Qiao et al. 2015).

When the basic model was defined, we separately added O_3, NO_2 into the basic model to estimate mortality effects of pollutants at individual lag day (lag0 to lag2) and moving averages of the current day and 1 and 2 prior days (lag01 and lag02). To examine the relationship between increased O_3 or NO_2 and mortality effects, we calculated four quartile values of O_3 and NO_2 concentrations at lag02 day (Q1:>25th; Q2:25~50th; Q3: 50~75th; and Q4:>75th). Percent changes of mortality at O_3 or NO_2 concentrations at Q2 or higher quartile were determined by comparing with that at Q1. We further estimated exposure-response relationship for O_3 and NO_2 on mortality by replacing linear terms with 3 DF.

Further, to assess changes in mortality effects of air quality improvement over 11 years' implementation of air pollution control measures in Guangzhou, we used two mortality burden indicators, including attributable fraction (AF, in %) and attributable mortality (AM, in number of death) that could capture variations of the onsets of air pollutant associated mortality effects. We evaluated AF and AM during periods of 2006-2010 and 2011-2016 for differential burden assessment over 11 years, in which the periods were stratified by 2010 Asian Games as before and after game. We further implemented a two-sample test for assessing statistically significant trend for the estimated AF between the two periods based on the point estimates and standard error (se) (Di et al. 2017). In addition, we estimated mortality burden attributed to O_3 and NO_2 exposure by each calendar year. The equations of AF and AM are shown below:

$$AF = \Sigma\{\text{baseline mortality}^* [\exp^*(\beta^*\Delta C)-1]\}/\text{overall mortality}$$

$$AM = \Sigma\{\text{baseline mortality} ^*[\exp(\beta^*\Delta C)-1]\}$$

Where AF is average attributable fraction of mortality during study period; AM is attributable mortality attributed to excessive O_3 or NO_2 exposure; baseline mortality is the daily mortality at a specific day; β is the mortality risk coefficients of O_3 or NO_2; ΔC is concentration difference between actual measurements and target levels below which no adverse health effects occurs, target levels were determined referring World Health Organization's (WHO) Air Quality Guidelines for O_3 of 100 $\mu g/m^3$ and for NO_2 of 40 $\mu g/m^3$.

And lastly, we compared mortality effects during the 2010 Asian Games in Guangzhou (November 12 to December 18, 2010) when enhanced air pollution control measures were implemented to a wintertime baseline period defined as

4-week before and 4-week after the Games. To test whether the variation in mortality effects was due to improved air quality, we selected accidental mortality as reference with expectations that there might be no change over periods. We further selected Zhuhai as the "control" city that would be unaffected by air quality measures during the game period. We used an interrupted time series analysis as follow:

$$Log(u_t)= \alpha_0+\alpha_1 period+DOW+Holiday+COVs$$

Where u_t is the daily mortality counts; period is defined as a dummy variable using "1" for the game period and "0" for the baseline period; DOW and Holiday are dummy variables for day of week and public holidays. COVs include temperature and RH with smoothing function and temporal trend.

Sensitivity analyses for robustness of main results were further conducted by: (1) using two-pollutant model with adjustment for other pollutants that were restricted by Pearson correlation coefficients < 0.6 to avoid multi-collinearity, (2) using polynomial distributed lag (PDL) model with a matrix of quadratic polynomial model to estimate mortality effects for cumulative exposures to air pollutants, (3) using case-crossover design with a three-way interaction term of year, month and DOW to control for time trend. In addition, we assessed the sensitivity to controlling for different temperature variables into models, including temperature at current day and 6 prior days to death (lag06), and a distributed lag non-linear model (DLNM) for temperature term (with a cross-basis matrix with 7 DF for both exposure and lag spaces and up to maximum lag of 14 and 21 days) (K Chen et al. 2018b; Gasparrini et al. 2015). Lastly, mortality burden attributed to $PM_{2.5}$ was assessed when considered target $PM_{2.5}$ concentrations of 25 μg/m^3 (WHO's Air Quality guidelines) and 75 μg/m^3 (Chinese National Ambient Air Quality Standards).

We separately constructed and assessed short-term mortality effects of O_3 and NO_2 at lag02 day as the main results. We expressed percent increase in mortality with its 95% confidence interval (CI) associated with each 10 μg/m^3 or interquartile range (IQR) pollutant increase. All analyses were performed in R software, version 3.4.2 (R Project for Statistical Computing, Vienna, Austria), using the "mgcv", "dlnm" packages. Statistical significance was defined as $p < 0.05$.

3. Results

Descriptive data statistics

Table 1 provides the descriptive statistics of daily mortality counts, levels of air pollutants and meteorological variables in Guangzhou, 2006-2016. The time-series plots of mortality and air pollutants are shown in **Figure S2**. Daily average death counts were 108, 41 and 18 for total and cardio-respiratory mortality, respectively. Daily average concentrations were 98.1 μg/m^3 for O_3, 32.5 μg/m^3 for NO_2 and 43.9 μg/m^3 for $PM_{2.5}$. Daily mean levels were 22.3 °C for temperature and 75.7% for RH. Among the pollutants and meteorological variables, O_3 was weakly correlated with $PM_{2.5}$ of 0.38 and with NO_2 of 0.14, $PM_{2.5}$ was moderately correlated with NO_2 of 0.67. Temperature and RH were negatively correlated with air pollutants, except for the correlation between temperature and O_3 (**Figure S3**).

Annual average concentrations of O_3, NO_2 and $PM_{2.5}$ during 2006-2016 in Guangzhou are shown in **Figure 1**. In specific, concentrations of NO_2 and $PM_{2.5}$ decreased over time, with decreased by 20.1% to 33.8 μg/m^3 from 2006 to 2016 in NO_2 (8.5 μg/m^3 reduction) and by 44.5% to 29.3 μg/m^3 (23.5 μg/m^3 reduction) in $PM_{2.5}$; however, O_3 concentrations remained at 90.3 μg/m^3 in 2016 with slight reduction in recent years.

Mortality effects of O_3 and NO_2 exposures over 2006-2016

Table 2 shows significant associations of O_3 and NO_2 exposures with increased mortality risks. We observed increases in total mortality of 0.60% (95%CI: 0.47, 0.74) and 1.89% (95%CI: 1.49, 2.29) in association with each 10 μg/m^3 increase in O_3 and NO_2, respectively. And stronger associations were observed on cardio-respiratory mortality, with the highest of 4.42% (95%CI: 3.16, 5.69) for cardiovascular mortality associated with an IQR increase in O_3. In addition, the associations remained robust in two-pollutant models and in other sensitivity analyses (**Table S3, S4**).

Table 3 shows that the relationship between O_3 or NO_2 and mortality increased stepwise at O_3 or NO_2 concentrations at Q2 or higher compared with those exposed at Q1. In specific, we observed percent increases of 2.88% (95%CI: 1.65, 4.11), 4.62% (95%CI: 3.19, 6.07) and 6.79% (95%CI: 5.14,8.47) in total mortality of O_3 exposed at Q2, Q3 and Q4 compared with those exposed at Q1, respectively. Increased mortality risks were also observed in association with each quartile increase in NO_2. **Figure 2** and **Figure S4** present approximately linear exposure-response relationships for O_3 and NO_2 on total and cardio-respiratory mortality.

Mortality burden changes of O_3 and NO_2 exposures over 2006-2016

We further estimated AF and AM of O_3 and NO_2 for the periods of 2006-2010 and 2011-2016 in **Table 4**. Specifically, estimated AF on total mortality attributed to O_3 was 0.88% (95%CI: 0.68, 1.08) in 2006-2010 and 1.03% (95%CI: 0.79, 1.28) in 2011-2016 (*P*-trend = 0.34), corresponding to AM on total mortality of 1590 deaths (95%CI: 1225, 1959) and 2574 deaths (95%CI: 1981, 3173). However, estimated AF on total mortality attributed to NO_2 were significantly decreased from 1.38% (95%CI: 1.09, 1.68) in 2006-2010 to 0.43% (95%CI: 0.34, 052) in 2011-2016 (*P*-trend < 0.001) and corresponding to AM on total mortality of 2496 deaths (95%CI: 1964, 3033) to 1073 deaths (95%CI: 846, 1301). Similar reductions in AF and AM attributed to NO_2 on cardio-respiratory mortality were also observed. Overall estimated AF and AM on total and cardio-respiratory mortality by calendar year are shown in **Table S5 and S6**. We observed decreases in mortality burden attributed to O_3 and NO_2 in recent years, with minimum AF on total mortality of 0.57% (237 deaths of AM) attributed to O_3 in 2013 and of 0.18% (72 deaths of AM) attributed to NO_2 in 2012. Additionally, similar methods were applied for estimating AF and AM attributed to $PM_{2.5}$ during periods of 2006-2010 and 2011-2016 as shown in **Figure S7**.

Mortality reduction during the 2010 Asian Games

Descriptive characteristic of daily mortality counts, daily levels of air pollutants and meteorological variables during the 2010 Asian Games and the baseline period are shown in **Table 5** and **Figure S5**. Reductions in 11.8% of PM_{10}, 11.4% of $PM_{2.5}$ and 0.02% of NO_2 were observed during the game period, and daily average total mortality counts also decreased from 121.7 to 102.9 (approximately 15.4% reduction).

Table 6 displays mortality benefits during the 2010 Asian Games compared with baseline period. After controlling for potential confounders, we observed significant decreases of 9.3% (95%CI: -15.0, -3.2) in total mortality and 16.0% (95%CI: -22.8, -8.6) in cardiovascular mortality, and non-significant changes in respiratory mortality and accidental mortality during the game period. Additionally, we compared potential mortality benefits at the same period in Zhuhai; however, non-significant mortality benefits were observed during the game period in comparison with those observed in the baseline period (**Table S8 and S9**).

4. Discussion

In present study, we observed significant air quality improvement in Guangzhou in recent years following unprecedented air pollution control implementation. During the study period, each 10 μg/m^3 increase in O_3 and NO_2 was associated with increases of 0.60% (95%CI: 0.47, 0.74) and 1.89% (95%CI: 1.49, 2.29) on total mortality, and the associations remained robust with adjustments for other pollutants. Following air pollution reduction, estimated AF attributed to NO_2 on total mortality decreased from 1.38% (2496 deaths of AM) in 2006-2010 to 0.43% in 2011-2016 (1073 deaths of AM). We also observed 9.3% (95%CI: -15.0, -3.2) reduction in total mortality during the Asian Games compared with those observed in the baseline period. Overall, our results provide strong evidence on mortality benefits from long-term and rigorous air quality improvement in study area Guangzhou, China.

We have observed substantial reductions in concentrations of NO_2 and $PM_{2.5}$ in Guangzhou, which are likely resulted from the effective implementations of national and regional air pollution control measures in China in recent years (Ma et al. 2016; Zhan et al. 2018; Zhong et al. 2013). The downward trend in NO_2 levels might reflect efforts of restrict vehicle emission control measures, as well as other air pollution control measures implemented in Guangzhou in recent years. However, we did not observe the reduction in O_3 levels, which was consistent with those reported in other Chinese cities (Cheng et al. 2018; Lu et al. 2018). It is worth to note that O_3 is mainly generated by nitrogen oxides (NO_x), VOCs and hydroxyl radicals in the presence of sunlight (Ou et al. 2016; Tao et al. 2012). Thus, the fluctuating high levels of O_3 in the Guangzhou might be due to unbalanced reductions in its precursors of NO_x or VOCs levels from anthropogenic sources, and warmer and drier meteorological conditions (Cheng et al. 2018; Fu et al. 2014; Zhong et al. 2018). Thus, O_3 has emerged as one of the greatest challenges in air quality management programme so that holistic measures for mitigating secondary pollutants have been included in current air pollution reduction action plans in the area in recent years (K Chen et al. 2018a).

We observed significant mortality effects for O_3, NO_2 during study period, which confirmed the consolidated evidence of adverse health effects of air pollution (Samoli et al. 2013; Tao et al. 2012; Tzima et al. 2018). We observed that each 10 μg/m^3 increase in O_3 and NO_2 was associated with increases of 0.60% and 1.89% in total mortality, with stronger associations for cardio-respiratory mortality, which were comparable to previous studies (Chen et al. 2017; Shang et al. 2013; Sun et al. 2018;

Yin et al. 2017). One meta-analyses included 33 studies for Chinese population reported 0.48%, 0.45% and 0.73% increases in total and cardio-respiratory mortality in association with a 10 μg/m^3 increase in O_3, and corresponding to 1.30%, 1.46% and 1.62% increases for NO_2 (Shang et al. 2013). However, a nationwide study evaluated association for O_3 on mortality in 272 Chinese cities reporting a 0.18% (95%CI: -0.11%, 0.47%) increase in respiratory mortality associated with a 10 μg/m^3 increase in O_3 (Yin et al. 2017). Overall, the difference of population size, study locations, analytic approaches or model specifications, as well as relative less numbers for specific mortality than total mortality might cause the heterogeneity in estimates among studies (Shang et al. 2013).

We observed almost linear exposure-response relationship between O_3 or NO_2 and mortality, which are consistent with previous studies (Chen et al. 2012; R Chen et al. 2018; Di et al. 2017). One study estimated exposure-response curves on the entire Medicare population in the United States during 2000-2012 and reported the linear relationship between O_3 and mortality with no threshold (Di et al. 2017). A study pooled exposure-response curves in 17 Chinese cities supported an approximately linear exposure-response relationship between NO_2 and mortality (Chen et al. 2012). Additionally, one study included 272 cities in China during 2013-2015 showed a linear relationship between NO_2 and mortality suggesting there still existed substantial health hazards even under the WHO Air Quality Guideline of 40 μg/m^3 (R Chen et al. 2018).

Both AF and AM have been widely accepted for estimating burden of disease attributed to excessive exposures to air pollutants, which were considered as suitable indicators for estimating potential health benefits from air quality improvement (Lin et al. 2016b; Wang et al. 2018). Majority of these studies focused on the mortality burden of excessive of ambient particulate matter exposure (Fang et al. 2016; Lin et al. 2016a; Lin et al. 2016b; Liu et al. 2018); however, fewer studies had evaluated the mortality burden of O_3 or NO_2 exposure (Linares et al. 2018; Lu et al. 2016). One study in Spain reported that an annual 6085 deaths on total mortality attributed to NO_2 applied WHO recommendation value of 20 μg/m^3 as target concentration (Linares et al. 2018). Another study evaluated mortality burden in PRD during 2010-2013 reported that 1271 and 1858 deaths on total mortality attributed to O_3 and NO_2, respectively in Guangzhou applied natural background concentration as target concentration (Lu et al. 2016). Consistently, in present study, we also observed that

1.38% of AF on total mortality (2496 deaths of AM) attributed to NO_2 in 2006-2010, and 0.43% (1073 deaths of AM) in 2011-2016, similar trends on cardio-respiratory mortality of NO_2 exposure were observed. However, significant mortality burden of air pollution remained indicating more stringent and rigorous air pollution control measures to be continuously implemented.

Accountability studies on health benefits following improved air quality actions or regulatory policies, often called as "natural experiments", have been emerging in recent decades (Clancy et al. 2002; Hedley et al. 2002; Rich et al. 2012; Tzima et al. 2018). Such studies could provide evidence of health benefits of temporary and long-term air pollution improvement or regulations, though the limitations of data availability and statistical considerations for causal inference remained (Rich 2017). Several studies applied this kind of study design and reported potential health benefits (such as reduction in mortality, hospital admissions) of air pollution reductions that resulted from employee strikes, governmental policies, large-scale sporting events and conferences (Clancy et al. 2002; Friedman et al. 2001; Hedley et al. 2002; Lin et al. 2014; Pope et al. 2007; Rich et al. 2012; Zhang et al. 2018). In present study, we applied a quasi-experimental design and assessed that potential mortality benefits could be gained through improved air quality during the 2010 Asian Games in Guangzhou. One study also reported significant decrease in total mortality with relative risk of 0.79 (95%CI: 0.73, 0.86) in comparison with the same period for four years before (2006-2009) and one year after (2011) (Lin et al. 2014). However, the special issue of the 2010 Asian Games was relatively short intervention period that might limit statistical power, as well as some confounding factors were not collected, such as smoking behavior, activity pattern, dietary style and medical quality that might influence our findings. Nonetheless, these factors were unlikely to change concomitantly during the game period. Additionally, we selected another PRD city of Zhuhai with similar economic and climate conditions as control city that provided the evidence of mortality benefits in Guangzhou (Tao et al., 2012).

Overall, several limitations should be noted. Firstly, inherent measurement errors in time-series study would underestimate estimates (Tzima et al. 2018; Wu et al. 2018). Secondly, we used average concentrations of pollutants from three air monitoring stations as exposure surrogates of general population which might cause potential exposure misclassifications and yield biased estimates. However, such limitations are unlikely to result in differential misclassification in exposure errors and tend to underestimate the effects toward null (Rich et al. 2012; Rich et al. 2015).

Conclusion

Exposures to O_3 and NO_2 were significantly associated with increases in mortality in Guangzhou, and remarkable reductions in mortality burden of air pollution exposures could be obtained from air quality improvement in recent years. Our findings provide strong evidence that air pollution control measures are effective in reducing ambient air pollutant levels and achieving health benefits in highly polluted region through comprehensive and rigorous air quality management practice.

Declarations of interest None.

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List of Figures

Figure 1. Annual average concentrations of O_3, NO_2 and $PM_{2.5}$ in Guangzhou, China, 2006-2016.

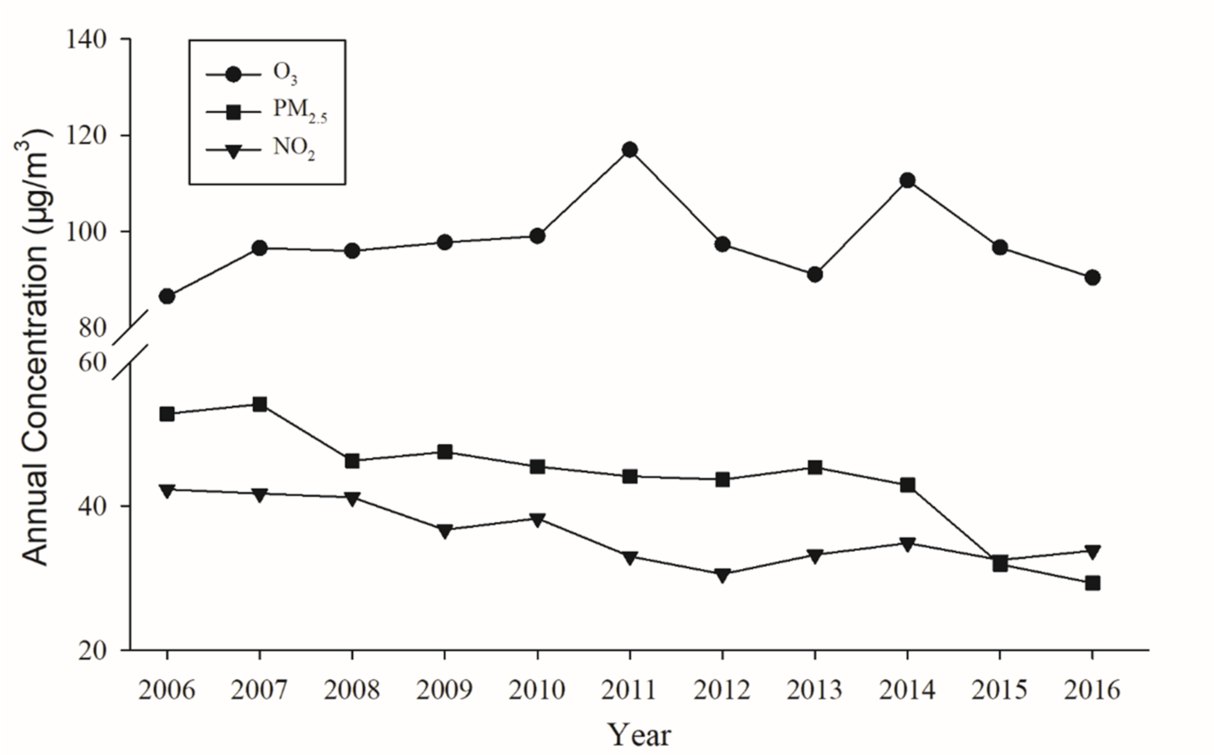

Figure 2. Estimated Exposure-Response Curves for total mortality associated with O_3 and NO_2. Solid black vertical lines represent IQR range of pollutant.

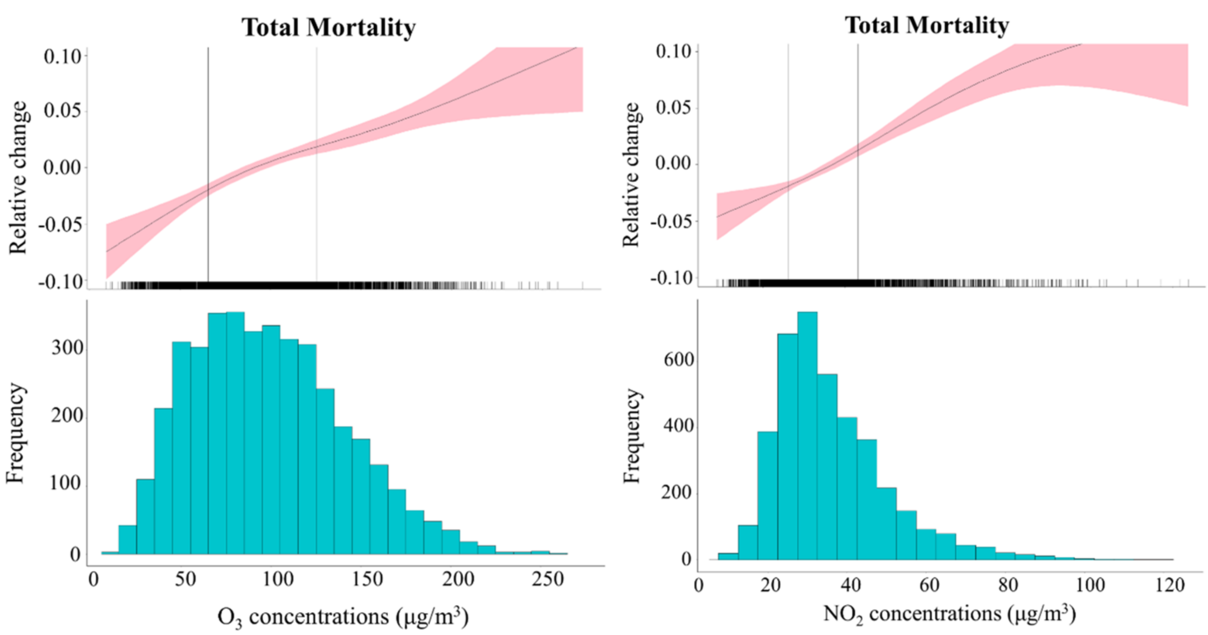

Table 1. Summary statistics of daily mortality counts, air pollutants and meteorological parameters in Guangzhou, China, 2006-2016.

Variables	Mean±SD	Min	Median	Max	IQR
Mortality (n)					
Total (non-accidental)	107.7±21.9	55	105	228	29
Cardiovascular	41.0±12.3	12	41	105	16
Respiratory	18.1±6.1	5	17	48	8
Air Pollutants (μg/m^3)					
O_3	98.1±48.6	3.3	92.8	292.7	70.5
NO_2	32.5±16.1	0.3	32.5	128.7	18.4
$PM_{2.5}$	43.9±23.2	4.0	39.6	235.9	29.3
Meteorological Parameters					
Temperature (°C)	22.3±6.3	3.4	23.9	33.5	9.6
Relative humidity (%)	75.7±12.4	25.0	75.7	100.0	27

n: number; SD, Standard deviation; O_3, daily maximum 8-hour Ozone; NO_2, nitrogen dioxide; $PM_{2.5}$, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm.

Table 2. Percent increases (95%CI), % in total and cardio-respiratory mortality associated with 10 μg/m^3 or IQR increase in lag 02 day O_3 and NO_2 in Guangzhou, China, 2006-2016, results from single- and two-pollutant models[a]

Pollutants	Method	Percent increase (95%CI), %					
		10 μg/m^3 increment			IQR increment		
		Total	Cardiovascular	Respiratory	Total	Cardiovascular	Respiratory
O_3	Single-pollutant model	0.60(0.47,0.74)	0.72(0.52,0.93)	0.68(0.39,0.97)	3.68(2.83,4.53)	4.42(3.16,5.69)	4.16(2.38,5.97)
	Adjusted for NO_2	0.40(0.25,0.55)	0.49(0.26,0.71)	0.42(0.10,0.74)	2.40(1.48,3.33)	2.95(1.58,4.34)	2.53(0.60,4.49)
	Adjusted for $PM_{2.5}$	0.39(0.23,0.55)	0.42(0.19,0.66)	0.43(0.10,0.77)	2.33(1.37,3.31)	2.55(1.12,4.01)	2.63(0.60,4.70)
NO_2	Single-pollutant model	1.89(1.49,2.29)	2.18(1.59,2.77)	2.29(1.46,3.12)	3.25(2.56,3.94)	3.75(2.73,4.78)	3.94(2.60,5.39)
	Adjusted for O_3	1.24(0.71,1.77)	1.14(0.36,1.93)	1.69(0.59,2.81)	2.41(1.66,3.16)	2.71(1.60,3.84)	3.07(1.50,4.65)

[a] Results from a generalized additive model with a quasi-Poisson, adjusted by time trend, temperature, relative humidity, day of week,

public holidays, influenza epidemics and annual population. Two-pollutant models were limited to pollutants with Pearson correlation coefficients < 0.6. IQR increment is 59.9 μg/m³ for O_3 and 17.1 μg/m³ for NO_2.

Table 3. Relationship between total and cardio-respiratory mortality and each quartile increase in lag 02 day O_3 and NO_2 exposure in Guangzhou, China, 2006-2016.

Pollutant	Quartile (μg/m³)[a]	Percent increase(95%CI), %		
		Total	Cardiovascular	Respiratory
O_3	Q1 (<65.6)	-	-	-
	Q2 (65.6~94.5)	2.88(1.65, 4.11)*	2.28(0.49, 4.11)*	4.82(2.27, 7.43)*
	Q3 (94.5~125.5)	4.62(3.19, 6.07)*	4.88(2.76, 7.03)*	6.96(3.97, 10.0)*
	Q4 (>125.5)	6.79 (5.14, 8.47)*	7.55(5.10, 10.06)*	9.18(5.73, 12.74)*
NO_2	Q1 (<26.1)	-	-	-
	Q2 (26.1~33.0)	1.45(0.26, 2.67)*	1.48(-0.29, 3.28)	2.69(0.96, 4.92)*
	Q3 (33.0~43.1)	3.14(1.81, 4.49)*	2.92(0.96,4.92)*	5.64(2.83, 8.53)*
	Q4 (>43.1)	5.54(3.96, 7.15)*	6.55(4.21, 8.95)*	8.39(5.04, 11.83)*

[a] Quartered by moving average of concentrations for 3 days of O_3 and NO_2 (lag02 day). Percent increases of mortality at Q2 or higher were determined by comparing with that exposed at Q1.

[b] $P<0.05$

Table 4. The attributable fraction (AF, %) and attributable mortality (AM, number of deaths) attributed to O_3 and NO_2 for periods of 2006-2010 and 2011-2016 in Guangzhou, China.

Mortality	Variable	O_3 (target at 100 μg/m^3)		p-trend	NO_2 (target at 40 μg/m^3)		p-trend
		2006-2010	2011-2016		2006-2010	2011-2016	
Total	Number	180868	249697				
	AF(95%CI)	0.88(0.68, 1.08)	1.03(0.79, 1.28)	0.34	1.38(1.09, 1.68)	0.43(0.34, 0.52)	<0.001
	AM(95%CI)	1590(1225, 1959)	2574(1981, 3173)		2496(1964, 3033)	1073(846, 1301)	
Cardiovascular	Number	63626	100199				
	AF(95%CI)	1.06(0.75, 1.36)	1.20(0.86, 1.55)	0.53	1.65(1.20, 2.11)	0.52(0.38, 0.66)	<0.001
	AM(95%CI)	671(480, 865)	1205(861, 1553)		1051(763, 1344)	521(379, 664)	
Respiratory	Number	30869	41499				
	AF(95%CI)	0.98(0.56, 1.40)	1.14(0.65, 1.64)	0.62	1.70(1.08, 2.34)	0.54(0.34, 0.73)	
	AM(95%CI)	301(173, 432)	525(332, 723)		474(271, 680)	222(141, 304)	0.001

[a] two-sample test for assessing statistically significant differences in the estimated AF between the two periods.

Table 5. Characteristics of daily mortality, air pollutants and meteorological variables during the 2010 Asian Games and the baseline period in Guangzhou, China.

Variables	Mean (SD)		Change (%)
	Baseline period[a]	Game period[b]	
Mortality (n)			
Total	121.7 (26.5)	102.9 (11.1)	-15.4
Cardiovascular	49.2 (14.0)	38.9 (7.1)	-20.9
Respiratory	21.3 (7.2)	17.3 (3.1)	-18.8
Accidental	5.4 (2.5)	5.1 (2.4)	-5.5
Air Pollutant (μg/m^3)			
PM_{10}	86.3 (31.3)	76.1 (24.6)	-11.8
$PM_{2.5}$	59.9 (22.4)	53.1 (17.9)	-11.4
NO_2	44.9 (17.4)	44.8 (10.5)	-0.02
O_3	114.6 (44.7)	120.6 (39.6)	5.2
Meteorological Parameters			
Temperature (°C)	16.7 (6.4)	18.5 (3.9)	10.8
Relative humidity (%)	58.6 (13.0)	63.6 (11.8)	8.5

n: number; SD, Standard deviation;
[a] Baseline period, defined as October 13-November 11 in 2010 and December 19 in 2010-January 19 in 2011
[b] Game period, defined as November 12-December 18 in 2010

Table 6. Univariate and Adjusted percent change (95%CI), % in daily mortality during the 2010 Asian Games compared with the baseline period in Guangzhou, China.

Outcome	Univariate (95%CI)[a]	*P* value	Adjusted (95%CI)[b]	*P* value
Total	-15.4(-21.7, -8.6)	<0.01	-9.3(-15.0, -3.2)	<0.01
Cardiovascular	-20.9(-28.9, -11.9)	<0.01	-16.0(-22.8, -8.6)	<0.01
Respiratory	-18.8(-28.2, -8.2)	<0.01	-9.1(-20.0, 3.3)	0.15
Accidental	-5.3(-21.7, 14.7)	0.58	26.8(-3.4,66.4)	0.09

[a] Results from Poisson model adjusted by indicator of period.

[b] Results from Poisson model adjusted by day of week, holiday, time trend, daily mean temperature and relative humidity

我国典型地区空气质量改善的健康效益评估及人群健康防护策略研究课题组

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主要研究方向为环境流行病学，包括空气污染的心肺系统健康损伤机制、风险评估、干预及政策制订等。自 2012 年起，担任世界卫生组织（WHO）环境健康顾问、专家组成员和课题负责人，参加和承担多项全球空气污染政策文件编纂和危害评估工作，主要包括空气污染致癌性评估、全球空气质量标准值更新、以及全球空气污染防护措施评估等。目前还担任 2021 年第 33 届国际环境流行病学会大会主席、国际环境期刊 Science of the Total Environment 副主编、Environmental Epidemiology 编委等职。此外，担任中国环境诱变剂学会青年委员会主任委员、国家室内空气质量标准修订工作组成员、国家环境基准工作委员会委员、欧美同学会留美医学委员会公共卫生专业委员会秘书长等职务。

此文章是国家自然科学基金 - 北京大学管理科学数据中心 2017 年资助课题“我国典型地区空气质量改善的健康效益评估及人群健康防护策略研究”的研究成果之一。该课题组负责人为北京大学公共卫生学院黄薇教授。该文章主要描述了广州市 2006-2016 年期间大气污染物中臭氧（O3）和二氧化氮（NO2）浓度水平变化特征，定量评估了大气污染物与人群死亡的急性暴露反应关系；并进一步根据广州市多年不同的空气污染防治措施，评估了广州市空气质量改善过程中归因于 O3 和 NO2 的死亡负担趋势；最后对 2010 年广州市亚运会期间的死亡效应的变化进行了分析。研究结果表明广州市空气质量的改善降低了大气污染相关死亡负担。

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